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Ocean Engineering For Ocean Thermal Energy Conversion

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OCEAN ENGINEERING FOR OCEAN THERMAL ENERGY CONVERSION

Panel on OTEC Ocean Engineering

Marine Board
Commission on Engineering and Technical Systems
National Research Council

National Academy Press
Washington, D.C. 1982

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This report has been reviewed by a group other than the authors according to procedures approved by a Report Review Committee consisting of members of the National Academy of Sciences, the National Academy of Engineering, and the Institute of Medicine.

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PREFACE

Origin of the Study

Ocean Thermal Energy Conversion (OTEC) is a technology for extracting energy from the stable and inexhaustible supply of solar heat stored in the surface waters of the ocean. When commercially developed, OTEC technology will use the temperature difference between warm surface and cold deep ocean water to power turbines via a heat engine. The turbines will power generators to produce electricity, for manufacturing at sea, or for transmission to shore. The development of OTEC technology is one of several solar energy research and development programs of the Department of Energy.

In response to a request from the National Ocean and Atmospheric Administration (NOAA) and the Department of Energy, the Assembly of Engineering of the National Research Council convened a Panel on OTEC Ocean Engineering under the auspices of the Marine Board.* Members were selected for their experience in design and construction of large ocean structures, naval architecture, environmental phenomena and environmental loading, marine geotechnical engineering, mooring systems, exploratory engineering, marine operations, and engineering systems integration. The principle guiding the constitution of the committee and its work, consistent with the policy of the National Research Council, was not to exclude the bias that might accompany the expertise vital to the study, but to seek balance and fair treatment. In particular, care was taken to ensure that panel members had not directly conducted OTEC research or development projects.

Scope of Study

The charge to the panel was to assess the state of ocean engineering knowledge, technology, and practice necessary to design, construct, and operate OTEC plants, especially in the areas of:

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*In a reorganization of the National Research Council in the Spring of 1982, the Assembly of Engineering was subsumed into the newly created Commission on Engineering and Technical Systems.

- Platforms, moorings and foundations, including floating (grazing or moored) platforms, and fixed systems (on dry land or mounted on the continental shelf).

- The sea water system and its interface with the OTEC plant, including pipeline configurations and floating or moored systems.

- Product transmission systems, especially the submarine electric power transmission cables and their interface with the OTEC plant.*

The panel was also asked to identify the additional ocean engineering research and development necessary to meet the objectives of the Department of Energy's OTEC program, and to make recommendations regarding the content and direction of ocean engineering R&D in the OTEC program. However, the panel stopped short of developing specific R&D programs. The panel was not asked to address the issues of power plant design and engineering, whether OTEC is a viable national energy option, or institutional and management arrangements in the development and implementation of the OTEC program, especially the appropriate roles of government and industry in the development of OTEC.

The panel focused its assessment of feasibility on a 40-megawatt electric (MWe) OTEC plant because, in the main, the technical information provided the panel for assessment addressed this size plant. It considered the scaling of OTEC ocean engineering technologies up to larger sizes and the feasibility of constructing and deploying larger plants. It also considered the technical advantages of smaller OTEC plants.

An important area of assessment for the panel was the adequacy of environmental design criteria, which are specific values of environmental parameters that describe the severity of natural events. Adequate environmental design criteria are important because they are used to determine the design forces and required support conditions for offshore structures.

To assist the panel, the NOAA prepared a compendium that set forth, through extracts and summaries of research reports, the technical status of the OTEC ocean engineering program, including the ocean engineering, related research and its findings, unresolved

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*The panel subsequently narrowed its assessment of product transmission systems to submarine electric cables because the technical base for assessment is better developed than that of other product transmission system concepts (see subsequent description of the technical baseline (page 8-12).

engineering issues, and research still required.* The numerous technical research reports that provided the basis of the NOAA staff report (and the baseline for the panel) are enumerated in the bibliography (pages 51-65). The scope and coverage of the NOAA compendium, and therefore the technical baseline of the panel's study, are described in the subsequent chapter titled "OTEC Ocean Engineering Development" (pages 7-12).

The panel, in carrying out its charge, used the technical information in the NOAA staff report, together with the research reports cited in it, as its technical baseline. It then validated the technical information (in the sense of confirming the evidence presented and conclusions drawn), conducted an assessment through meetings and a workshop, and rendered expert opinions based on the review, and the experience of panel members.

Study Organization

At the outset, the panel reviewed the NOAA compendium, and invited other experts to review it. The reviewers are listed in Appendix A. The reviews were used by the panel in developing written critiques of the NOAA compendium that identified outstanding technical issues in OTEC ocean engineering.

The panel then convened a workshop with invited experts to identify omissions, deficiencies, and discrepancies in the technical information; describe major technological problems and issues; identify needed research; and establish the technological priority and timing of remaining ocean engineering development. Participants in the workshop are listed in Appendix B.

The panel's report, and conclusions and recommendations are based on its review of the NOAA compendium together with the research reports listed in the bibliography, on the technical assessment of the current state of OTEC ocean engineering conducted at a workshop, and on the professional experience of panel members.

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*The NOAA compendium is available on request from the Marine Board, National Research Council, 2101 Constitution Ave., N.W., Washington, D.C. 20418.

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SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

Ocean Thermal Energy Conversion (OTEC) is one of several solar energy programs of the Department of Energy. The Panel on OTEC Ocean Engineering of the National Research Council was formed to assess the state of ocean engineering knowledge, technology, and practice necessary to design, construct, and operate OTEC plants. The panel concentrated its study on platforms, moorings, and foundations; the cold water pipe; and submarine cables for electric power transmission. The panel did not address the design and engineering of power plants; institutional and management issues or the commercial feasibility of OTEC; or its environmental impacts. The panel focused instead on determining the state of development of several of the ocean engineering technologies needed to design and construct a 40-MWe OTEC plant; it also examined the technical feasibility and advantages of larger and smaller plants.

Assessment of the State of Practice of OTEC Ocean Engineering*

The design, construction, and installation of land-based and shelf-mounted OTEC plants producing up to 40 MWe is technically feasible from the standpoint of ocean engineering. The necessary ocean engineering research and development has been identified and can be completed in a reasonable time period to support OTEC system development.

For a 40-MWe floating plant, the submarine electric cable system requires the most development. For all OTEC configurations, major questions arise about the ability to construct plants larger than approximately 40 MWe. The extent to which the cold water pipe and the submarine electric cable systems can be enlarged beyond the size needed in a 40-MWe plant needs to be demonstrated; upper limits on their size are not established. For floating plants, the difficulty

*The term "state of practice" means that no additional ocean engineering research is necessary; the issue is confined to a design problem.

of engineering development required for submarine electric cable systems could preclude commercial feasibility of providing power by cable to land for many years. Thus, technical considerations indicate that, for floating plants, smaller sizes (up to 40 MWe) may be more feasible.

RECOMMENDATION: The advantages of constructing and operating smaller OTEC plants (up to 40 MWe) should be established, and possible applications pursued.

Systems Integration

Many of the remaining engineering issues for OTEC depend on the engineering necessary to integrate the system components that have been separately engineered. These components include power plants, platforms, moorings, foundations, sea water systems, and submarine electric cable systems. Engineering studies have not adequately addressed the design of critical interfaces between system components, and such interfaces' construction, installation, inspection, maintenance, and repair. These interfaces, and procedures relating to them, require further examination. Site specific design and development studies of total systems are also important for systems integration.

RECOMMENDATION: The Department of Energy should strengthen the technical coordination between its ocean engineering development for OTEC and the other elements of its OTEC program.

Needed Research and Development

Additional research and development in ocean engineering is necessary for the advancing of OTEC technologies. The specific work needed on platforms, moorings, foundations, the cold water pipe, and the submarine electric cable, is summarized in Table 1.

RECOMMENDATION: Should the development of OTEC technologies be continued, necessary ocean engineering research and development should be undertaken. The content and timing of research programs should be coordinated with other OTEC system development with special regard to the definition of design requirements, selection of OTEC plant sites, and integration of OTEC systems.

OTEC Program Content and Direction

Specific design requirements of the government's OTEC program (performance, reliability, and maintainability objectives for the design, construction, and operation of OTEC systems) need to be adequately and completely defined. The lack of clearly defined design requirements complicates the identification and solution of needed ocean engineering development.

RECOMMENDATION: The design requirements of the OTEC program should be made clear by the Department of Energy in a statement that is updated periodically and made available to researchers, contractors, and vendors.

Catalog of Applicable Research Results

Important and broadly applicable engineering research has been conducted in the OTEC ocean engineering program. While virtually all of this information is in the public domain, it is not readily available.

RECOMMENDATION: Regardless of the future of the OTEC program, the results of the OTEC ocean engineering development program should be summarized, indexed, and catalogued so that they will be accessible to other users. This documentation should include information about discarded concepts.

Table 1 Importance and Difficulty of Needed Ocean Engineering Research and Development*

Specific Area of Interest	Applicability**	Importance***	Difficulty***
Platforms, Moorings, and Foundations			
1. Integrate industrial process design requirements with ocean engineering	Land/Shelf/ Moored/Grazing	H	L
2. Determine the impact of the submarine electric cable on system mooring requirements	Moored	H	L
3. Evaluate foundation installation on steep slopes, especially in deep water; evaluate slope stability****	Land/Shelf/ Moored	M	H
4. Analyze and verify hydrodynamic motion response of prototype designs	Moored/Grazing	M	M
5. Determine the effect of high voltage transmission on platform materials and corrosion devices	Shelf/Moored/ Grazing	M	M

* Importance refers to the relative importance of the ocean engineering issue for the further development of OTEC. Difficulty refers to the severity of the ocean engineering issue in terms of the time and cost required to resolve it.

** Land, shelf, moored, or grazing OTEC. See pages 12-21 for an explanation of these various design concepts.

*** High, Medium, Low.

**** Importance and difficulty are site specific.

Table 1 Importance and Difficulty of Needed Ocean Engineering Research and Development (Continued)

Specific Area of Interest	Applicability	Importance*	Difficulty*
Sea Water Systems			
1. Gimbal design: working life, maintainability, and dynamics	Moored/Grazing	H	M
2. Isolate pipe water mass dynamics from the platform	Moored/Grazing	H	M
3. Design vortex-induced vibration suppression devices	Shelf/Moored/ Grazing	H	M
4. Fiberglass-reinforced plastic: determine long-term material properties, maintainability	Land/Shelf Moored/Grazing	H	M
5. Calibrate analytical tools for predicting dynamic behavior	Moored/Grazing	H	L
6. Pipe deployment: develop procedures, constraints on design, site specific considerations	Land/Shelf Moored/Grazing	M	L
7. Develop procedures for inspection, maintenance, and repair	Land/Shelf Moored/Grazing	M	L
Submarine Cable System			
1. Develop cable design specifying material, fatigue, torque, weight, slippage, corrosion characteristics	Shelf/Moored	H	H
2. Develop gimbal design regarding both structure and installation	Moored	H	H

*High, Medium, Low

Table 1 Importance and Difficulty of Needed Ocean Engineering Research and Development (Continued)

Specific Area of Interest Electric Cable (cont'd.)	Applicability	Importance*	Difficulty*
3. Develop inspection, maintenance, and repair concepts and equipment (including field splice capability)	Shelf/Moored	H	H
4. Make prototype validations	Shelf/Moored	H	M
5. Analyze deployment and recovery	Shelf/Moored	M	L
6. Calibrate analytical tools for analysis of cable designs	Shelf/Moored	M	L
7. Design and test devices to suppress vortex-induced vibration	Shelf/Moored	M	L
8. Develop armoring or burial cable protection	Shelf/Moored	M	M

*High, Medium, Low.

OTEC OCEAN ENGINEERING TECHNOLOGY DEVELOPMENT

Federal support for OTEC development began with the National Science Foundation in 1972. The OTEC program was transferred to the Energy Research and Development Administraton in 1975, and to the Department of Energy (DOE) in 1977. Within the Department of Energy, the OTEC Program is housed in the Office of Solar Technology.

The DOE/NOAA OTEC Technology Development Program

Since 1977, the National Oceanic and Atmospheric Administration (NOAA) has provided technical, engineering, and management assistance to DOE in developing ocean engineering technology for OTEC applications. The major elements of NOAA's work have been the development of concepts for OTEC platforms or vessels; seawater transfer systems, including the large cold water pipe; and mooring and foundation systems. The development of the submarine electric power transmission cable system has been managed separately by the Department of Energy as a high voltage cable design task. It has not to date been managed as a critical ocean engineering item requiring ocean engineering research and development

The OTEC ocean engineering technology development effort, which is managed by a program management office within the NOAA Office of Ocean Technology and Engineering Services, is intended to demonstrate the technical and economic feasibility first of a pilot plant of about 40 MWe, leading to plants of 100 MWe or larger.

The OTEC ocean engineering technology development program has been directed at the development of viable platforms or vessels; sea water transfer systems, including the large cold water pipe; and mooring and foundation systems. The work undertaken has included analysis, laboratory tests, at-sea tests and evaluations, and some studies of systems. Analyses have been conducted of the entire system as well as of the individual components. Analytical computer codes have been generated to validate the motion response and structural integrity of the platform, power system, and cold water pipe designs.

Laboratory research has been done on the properties of lightweight concrete and fiberglass-reinforced plastic. The laboratories have also conducted small-scale model tests of the platform, cold water pipe, and mooring systems arrangements to provide data on response to at-sea conditions. Theoretical projections of these systems are to be experimentally verified by at-sea model tests on a scale of one-third to one-fourth of that projected for the 40-MWe plant.

In 1982, the DOE funded the first phase of a cost-shared program for the design, construction, and operation of a 40-MWe OTEC pilot plant to demonstrate the commercial viability of OTEC. Two conceptual designs, one for a land-based plant, the second a shelf-mounted plant, are currently being developed. Both designs have facilities to generate electric power and cold water pipes that extend along the continental slope in a pipeline configu- ration down to deep water.

Technical Baseline for the Study

To support the work of the panel and to provide the technical baseline for the study, NOAA prepared a compendium of the OTEC ocean engineering research and development that has been undertaken by the government program in the last several years. The compendium covers the following major topics:

- o Top level requirements on ocean engineering technology
- o Platforms
- o Sea water systems, including cold water pipe
- o Moorings and cables
- o Electric cable and product delivery

Each of the five sections in the compendium summarizes, excerpts, and references the many research studies, preliminary designs, and laboratory and field tests that have been undertaken, and presents a technical assessment in accordance with the following general outline:

- o Present technology (state of practice/research undertaken)
- o Major findings
- o Remaining technical issues/problems
- o Research needed

Five appendices, three additional papers, and an extensive bibliography are included in the compendium to supplement the material presented in the technical summary/background papers. These include:

Appendices

A. OTEC Ocean Engineering Technology Development [Paper]

B. Environmental Data for OTEC Sites [Report]

C. 40-MWe Baseline Design for Moored Floating Plant [Report]

D. 40-MWe Baseline Design for Grazing Floating Plant [Report]

E. 40-MWe Baseline Design for Shelf-Mounted Plant [Report]

Supplementary Reading (Papers)

- Design and Analysis of OTEC's Cold Water Pipe
- OTEC Mooring System Development
- Assessment of Existing Analytical Tools for Predicting Cold Water Pipe Stresses

Top Level Requirements Section

This section covers the physical background and history of OTEC system development and summarizes recent U.S. system and major subsystem development projects. The compendium clearly indicates that while 100 to 400-MWe plants are considered appropriate for commercial application within the continental United States, current goals are to design, build and operate "pilot" or "proof of concept" plants of 10 to 40-MWe generating capacity. Further, the major emphasis has been on plants of 40-MWe capacity. Such plants could well serve in a commercial capacity for many island installations.

Design goals and constraints guiding OTEC technology development include:

- Power Output 40-MWe pilot or proof of concept plant.
- Operability full power operation in seas up to state 6 (i.e. significant wave height about 6 meters).
- Availability 90%, e.g. as more than 10% downtime for environmental factors, maintenance and repair.

- <u>Survivability</u> 100 year storm at operating site without leaving mooring.

- <u>Life</u> 30 years for commercial systems.

The compendium describes how five locations initially were considered especially appropriate for OTEC plants: Keahole Point, Hawaii; Punta Yeguas, Puerto Rico; New Orleans, Louisiana; the West Coast of Florida; and an area in the South Atlantic off the Coast of Brazil. Other sites noted include the island of Guam, and an area off the northwest coast of St. Croix, Virgin Islands. The compendium notes that emphasis has been placed on the Hawaiian, Puerto Rican, and South Atlantic sites. It also describes that, while operational tests have been conducted 14 miles northwest of Keahole Point, studies now are concentrating on sites on or close to Kahe Point, Oahu, Hawaii because of favorable environmental conditions, and proximity to load centers of adequate size to accept the output of a pilot plant without serious disruption should outages occur.

Platforms Section

The "platforms" section of the compendium describes studies by three contractors who considered six generic hull forms: ship (or barge), cylinder (or disc), sphere, spar, submersible, and semi-submersible. Each contractor further developed two of its preferred designs and finally selected a preferred concept. This exercise resulted in two ship (or barge) and one spar concept being proposed for further consideration for floating plants.

In each design the cold water pipe was supported by and suspended beneath the platform. Only cursory consideration was given to separately supported cold water pipes which could be largely de-coupled from platform motions. Proposals for the critical platform/pipe connection included spherical and hinged joints of various designs, and rigid connections.

Power plant sizes ranged from 50 to 500-MWe capacity in initial studies, then narrowed to 40-MWe capacity in later phases of the NOAA platform studies program. Parallel studies were made of 10- to 40-MWe capacity land-based plants located at Keahole Point, Hawaii and Punta Tuna, Puerto Rico.

Seawater Systems Section

The sea water systems section describes the various system design studies, material testing programs, laboratory and at-sea model test programs, as well as the development of computer-aided tools for design and analysis of cold water pipes 10 to 30 meters in dia-

meter. Suspended pipes would be up to 1000 meters long, while pipes installed along the ocean floor for land-based or shelf-mounted plants could be up to 6000 meters long. Suspended pipe designs include rigid, flexible, articulated joint, multiple pipe, and tension leg moored pipes. Shelf-mounted pipe designs include a variety of foundation design and installation techniques.

Pipe materials considered included steel, concrete, elastomers, and fiberglass or fabric reinforced plastics. Studies addressed structural design and response, material properties, corrosion, susceptibility to fouling, fabrication, and cost.

Other sea water systems studies that are summarized in the compendium include the quantification of hydrodynamic and platform induced loads, which include vortex shedding and shedding suppressor designs, and also the development of a hydraulic/dynamic model of seawater systems; platform attachments and pipe joints; pumps; fabrication, deployment, recovery and survival techniques; and inspection, maintenance and repair procedures.

Moorings and Foundations Section

The moorings and foundation studies described in the compendium consider three basic concepts: catenary leg concepts, tension leg concepts, and bottom-mounted platform concepts. Catenary and tension leg concepts included both single and multiple anchor leg moors. Four categories of anchors were considered: drag embedment, dead weight or gravity, pile, and plate. Chain, wire rope, synthetic rope, and steel tubing were considered as potential mooring cable materials.

Studies address the availability of analytical tools for mooring and foundation design including the determination of environmental loading, response, reliability, and failure analysis. Manufacturing, deployment and handling considerations, and inspection, maintenance and repair techniques also are addressed.

Electric Cable and Product Delivery Section

Studies summarized in the compendium address power transmission cable systems as two subsystems: a transition or riser cable system linking the platform to a sea floor-mounted junction box, and a bottom cable system from the junction box to a shore grid. Problems addressed include: cable strength member fatigue, cable termination at the platform to decouple cable and platform motions, electrical core protection, deployment, dielectric service life, subsystem interfaces, and cable system modeling.

Although economic studies of the production of energy-intensive products offshore from an OTEC plant ship are summarized, only the most cursory attention is given in the NOAA compendium to technical problems associated with the design, construction, installation and operation of such production plants on floating platforms. These plants, as well as the basic OTEC plant (evaporators, turbines, condensers, generators, and associated auxiliaries) have not been addressed by NOAA as embodying "ocean engineering" technical problems. Consequently they are not discussed in the compendium, and are not considered to be a part of the charge to the Panel on OTEC Ocean Engineering.

The compendium was distributed to all panel members and to an extensive list of other experts in relevant technical fields for review, validation (to confirm from their own knowledge and experience the soundness of conclusions drawm from the evidence presented), and assessment of the availability of the required ocean engineering technical tools and data necessary to design, build, install and operate with reasonable technical risk a pilot OTEC plant of up to 40-MWe generating capacity.

The invited reviews resulted in an additional body of information which also was used by the panel in its deliberations and in preparation of its final report.

The compendium on OTEC Ocean Engineering is available on request from the Marine Board.

PLATFORMS, MOORINGS, AND FOUNDATIONS

Design Choices

Platforms

There are a number of platform options for basing OTEC plants. These include shore-based structures, platforms mounted on the continental shelf, and floating platforms. Floating platform configurations might include ship or barge-type hulls, semisubmersible hulls, or spars. Each of these may be moored or untethered. The cold water pipe may attach directly to the platform, or it may form a separate structure incorporating the mooring system and attach to the platform by a flexible bridging system. Each of the possible platforms offers the system designer certain advantages and disadvantages for meeting site-specific environmental requirements and for accommodating all of the major elements of an OTEC system: the industrial (power) plant, the cold and warm water intake and discharge piping and circulation pumps, and the energy use or transmission system (see Figure 1).

<u>Land-Based Plants</u> A land-based plant (Figure 2) can utilize conventional industrial plant structure to house its power plant elements, or a barge-mounted configuration, similar to that designed for offshore nuclear power plants, which can be floated into a prepared land site and back-filled in place. Both offer the power plant designer relatively unrestricted options for arrangement and uncomplicated construction. Both also allow easy access to power plant elements for routine inspection, maintenance, and repair during the operating life of the system. The electric power they generate can be fed directly to a grid using conventional tower-mounted high voltage lines. Or, energy intensive industrial operations can be sited near the power plant.

Ocean engineering problems for these systems are confined to the seawater supply and discharge systems. The major design problem arises from the length and diameter required of the cold water pipe. For pipes running to about 200 water depth, designers can draw from state of practice sewer outfall and tunnel techniques to solve surf-zone and shelf-zone design and construction problems, provided sites are chosen that have adequately stable slopes. The installation of outfalls and tunnels on slopes in water depths of 200 to 1000 will require advances in the state of practice. Further, the cost of installing such a pipe or tunnel would certainly be high.

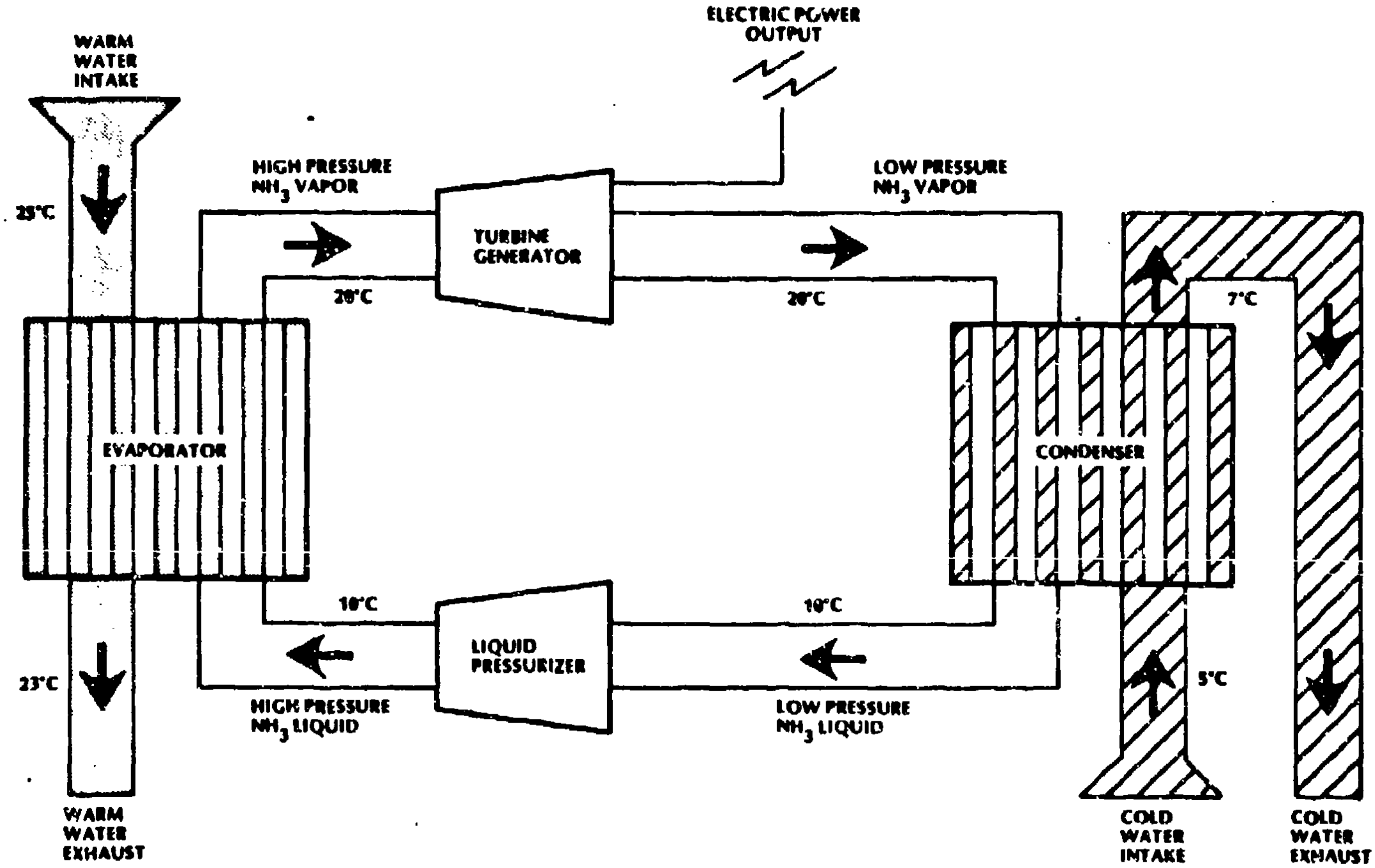


Figure 1 The OTEC Power System

SOURCE: Sullivan, S. M., M. D. Sands, J. R. Donat, P. Jepsen, et al., Environmental Assessment Ocean Thermal Energy Conversion (OTEC) Pilot Plants, Lawrence Berkeley Laboratory, University of California, Berkeley, California, 1981. Report No. LBL-12328 Rev., U.C.-64, DOE/EA-0147.

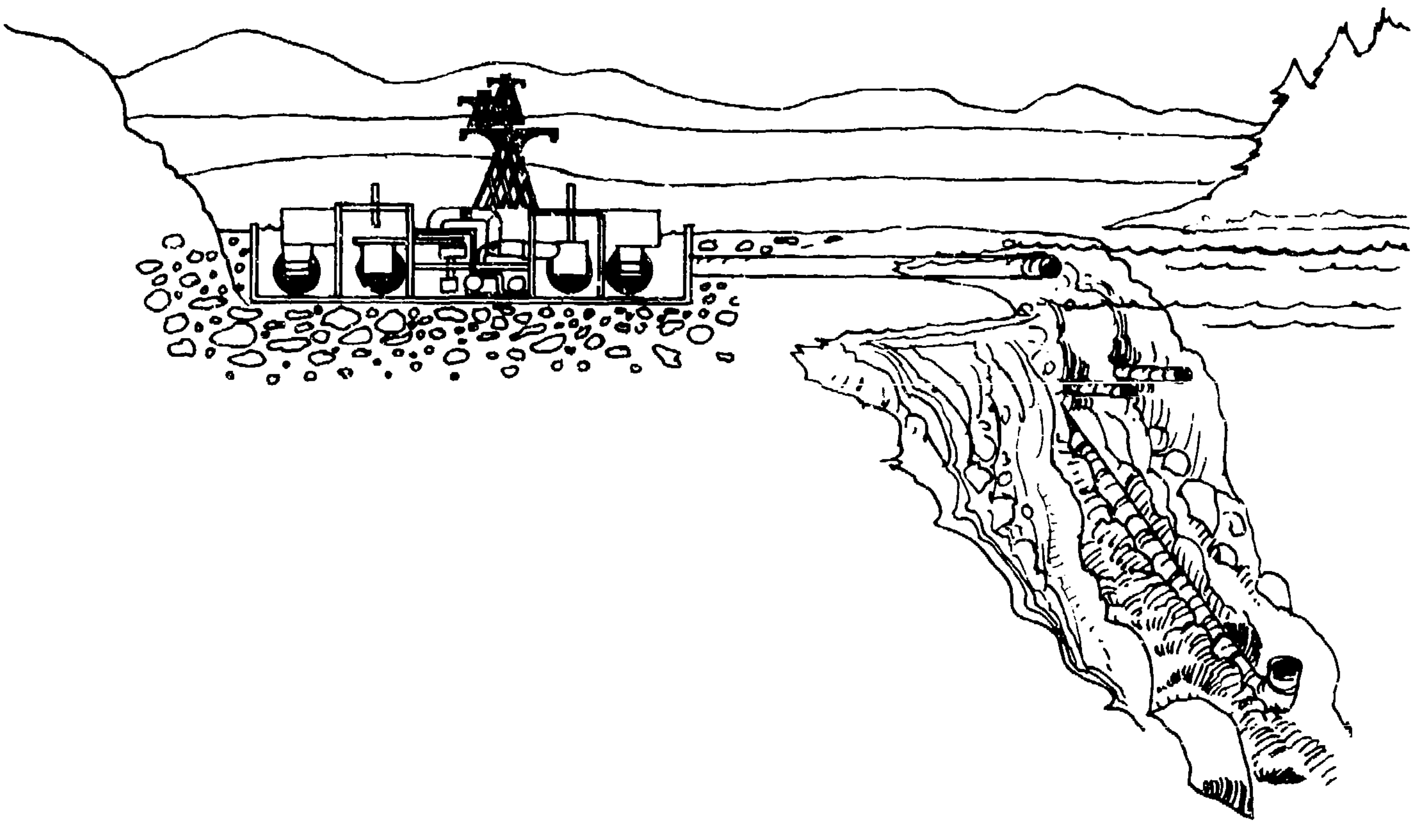


Figure 2 Land-based OTEC plant

SOURCE: Final Environmental Impact Statement for Commercial Ocean Thermal Energy Conversion (OTEC) Licensing, Office of Ocean Minerals and Energy, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, Washington, D.C., 1981, p. 1-11.

It should be noted that heat exchangers (evaporators and condensers) must be located below sea level to avoid hydrostatic power losses associated with lifting above sea level the enormous quantities of sea water required for an OTEC plant. In recognition of the above, a feasibility design study of land-based OTEC plants shows the heat exchangers located in deep excavations with their tops just at sea level.[1]

Shelf-Mounted Platforms A shelf-mounted platform requires a structure comparable to oil-field drilling and production platforms, with a few key differences. Designs for these platforms have been developed by the offshore oil and gas industry. Related structural design and engineering practices and tools are established. The deepest water in which steel jacket platforms can be used for OTEC is believed to be about 350. Articulated structures such as tension-leg platforms, which are being introduced in the offshore oil fields, may allow the emplacement of a shelf-mounted OTEC plant in deeper waters.

Typical offshore platforms have major blocks of superstructure placed well above the waves. In fixed offshore platforms for OTEC, the large power plant housings will have to be located in the water column to reduce hydrostatic power losses. This will create a new situation relative to hydrodynamic loads, but techniques are available to evaluate and design for such loads and stresses. Placing the heat exchangers just below sea level would put them directly in the surface zone where wave and current forces are greatest.

Consequently it may be preferable to place the heat exchangers well below the surface, an arrangement that will make installation and maintenance more difficult as discussed below.

The shelf-mounted design approach eliminates problems resulting from the relative motion of platform and cold water pipe, and platform and submarine electric cables, but it presents formidable problems to the power plant designer. If all power system elements are to be close-coupled to maximize the efficiency of the heat engine system, there will be increased demands on structural designers to develop dry housing for the turbo-generator. If all plant elements requiring dry atmosphere are located on the superstructure, long vapor and condensate leads will be required from the submerged heat exchangers, with consequent losses in efficiency. The tolerability of such losses can be established only through careful system design of the power plant. Whether all or only some of the power system elements are located below water, their installation and subsequent periodic removal for inspection, maintenance, and repair will require the development of complex mechanical devices to permit remote isolation of gas passages, disengagement of pipe joints, and removal, reinstallation, and purging of equipment prior to resuming operation. Alternatively, divers would be required virtually full time to operate less

complex closure and isolation systems. In designs that call for submerged dry spaces, hazards to operating personnel from leaks of ammonia or other heat exchanger fluid will be greater.

Compliant Structures Recent advances in tension-leg mooring concepts and articulated towers offer the potential for adopting such concepts in a combined cold water pipe and mooring system separate from the platform (Figure 3). While the size of pipes needed to carry cold water over to the platform will demand significant engineering development for the rotary joints or hinge-point flexural elements (or both) required to decouple the motions of the platform from that of the head of the cold water pipe/mooring system, the benefits of such development could be significant. Such development might rely in part on the very large mooring/cargo transfer yokes already designed and built for single-leg mooring systems to accommodate offshore tanker loading.

Floating Structures Conventional ship or barge-type hulls offer a simple configuration for floating platforms. They can be built of steel or reinforced concrete and outfitted with OTEC power plants in existing shipyard facilities on either coast or in the Hawaiian Islands. Their form offers the simplest problems of plant arrangement for the power plant designer. Ready access can be provided for the installation of all power plant elements and their removal for inspection, maintenance, and repair. Hazards to operating personnel from working fluid leaks can be minimized. The motions of conventional hull forms will be more severe than those of other floating forms, but these motions do not pose insurmountable problems. In some situations, a separate single-point mooring/cold water pipe system which permits weather-vaning could reduce the motion response of the platform as well as permit decoupling of platform motion from that of the cold water pipe.

Semisubmersible platforms offer significantly reduced motion characteristics compared with ship-like forms. They too can be constructed in existing shipyard facilities using steel as a structural material. The configuration of these platforms presents more difficult problems of arrangement to the power plant designer than does a ship-like form, but ballasting arrangements could be made that would permit dry access to all power plant components for inspection, maintenance, and repair. Because of the small water plane areas that make such platforms relatively unresponsive to elevated sea states, these platforms are also quite sensitive to weight changes and require very careful weight control procedures. The hazards to operating personnel from working fluids on these platforms would be comparable to those of ship-like plants.

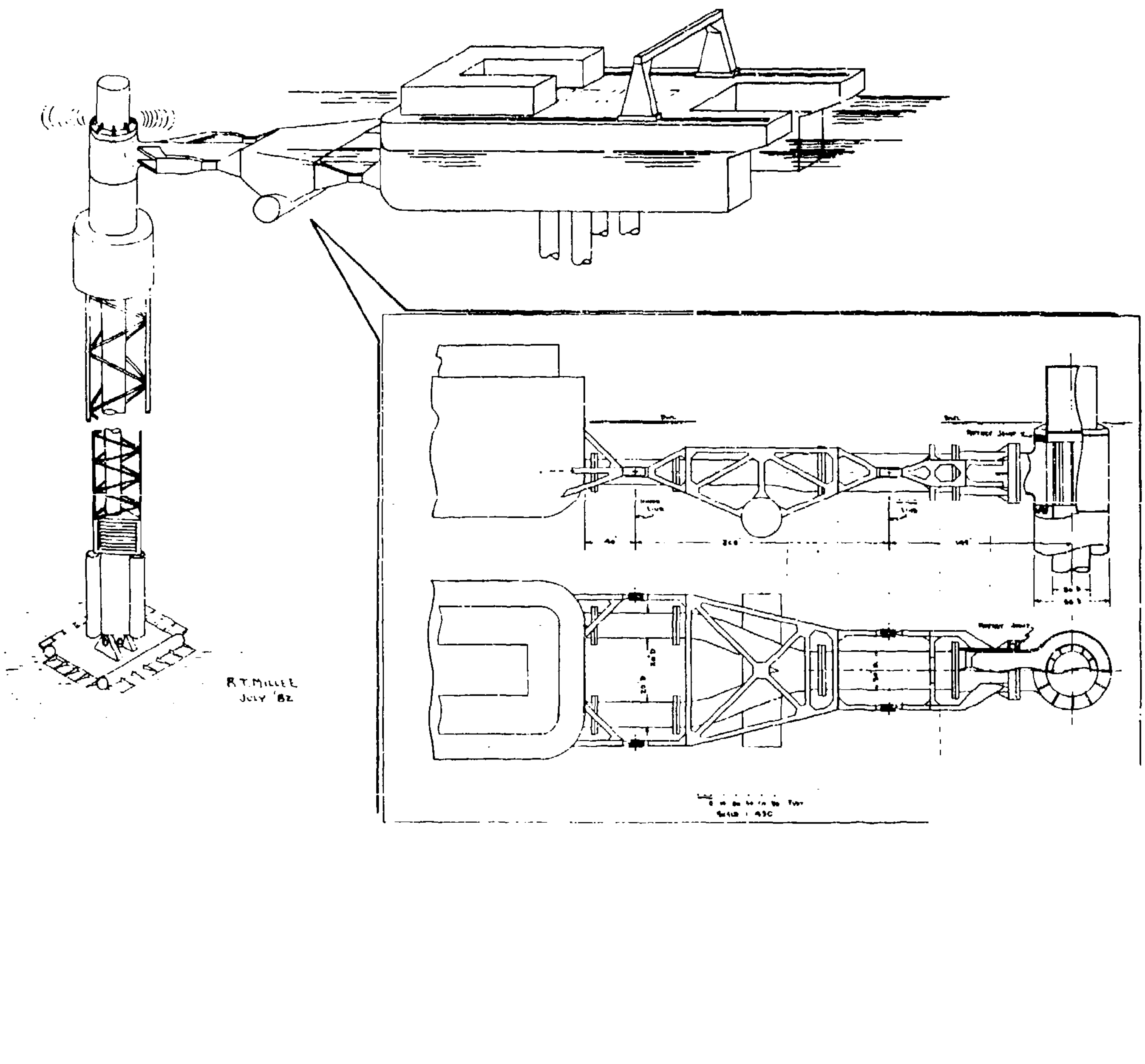


Figure 3 Cold water pipe yoked to floating OTEC plant

Spar configurations offer the least motion response, but at significant cost in other features. Their construction would require special sites and facilities not readily available in the United States. Arrangement of power plant components will be even more spaceand weight-limited than on semisubmersibles, and access for inspection, maintenance, and repair will be restricted. Modular units, designed to permit attachment of heat exchanger elements at sea, would ease overall construction and emplacement problems, but would offer formidable ocean engineering problems for the units' transport, installation, and subsequent removal for inspection, maintenance, and repair. The very small water-plane area of this configuration would make it extremely sensitive to weight changes, thus creating a critical weight control problem. Because of the small reserve buoyancy in the design, such configurations are more vulnerable to loss from collision damage. As with other designs that call for submerged dry spaces, potential hazards to operating personnel from heat exchanger fluid leaks will be accentuated.

Most development effort for floating plant concepts has concentrated on cold water pipes directly connected to the platform. Only cursory studies have been made of separately supported cold water pipes that have bridging systems to carry the water from the top of the pipe to the platform, as in Figure 3.

Foundations and Moorings

For each of the OTEC design configurations, one of several mooring and foundation designs may be used. Mooring systems may rely on drag embedment, gravity anchors, or piles. Foundations may employ a gravity design, or be pile-supported. In general, the options of the OTEC designer are similar to those available or planned for offshore petroleum structures.

The design of mooring and foundation systems is site dependent because of differing environmental conditions and seafloor topography. For installing a cold water pipe on the seabed as a pipeline, gravity or pile-supported foundations may be used.

Assessment of Technical Issues

Power Availability and Plant Service Life

While a 40-MWe prototype OTEC system can likely be designed for a 30-year service life, the production of power at least 70 percent of the time (that an adequate ocean thermal resource exists) will be very difficult to achieve. The electric utility industry now has power available 50 to 70 percent of the time from most of its nuclear and

fossil fuel units. Assuming the OTEC power turbines and generators can provide 70 to 80 percent availability, the rest of the system--the physical structure and its mooring or foundation, the sea water system, the heat exchangers, and the submarine electric cable systems--must achieve an availability which exceeds 90 percent if the overall system is to have power available 50 to 70 percent of the time. Consequently, the OTEC system elements must be designed, constructed, and operated so that they are highly reliable and easily maintained. Even then, the design goal of 70 percent plant availability may be very optimistic.

Mooring System Service Life

Elements of the mooring system will be subjected to severe corrosion, erosion, and fatigue, and will require periodic replacement to achieve a 30-year system service life. Inspection, maintenance and repair inspection, maintenance, and repair procedures need to be developed in the initial design. These procedures must take account of fatigue, corrosion, and erosion characteristics of the best available materials for the service intended. Inspection, maintenance, and repair procedures will need to be refined and amended as operating experience is obtained.

Hydrodynamic Motions and Environmental Forces

Control of pitch, roll, and heave responses to environmental forces can be achieved through conventional platform design. Rotating machinery and other power system components can be designed to tolerate expected platform motions with normal marine engineering practices. Such motions should have no adverse effect on the ability of personnel to perform assigned tasks. Nevertheless, to guide designers of power plants and other major subsystem components designers (for example, moorings, water intake and discharge pipes, and electrical power transmission subsystems), achievable motion responses need to be determined early in the design process.

The environmental forces that will affect system motion and generate response loads are highly site specific. Consequently, they must be determined accurately prior to the initiation of system design.

Analytical techniques have been developed that can predict the dynamic response of the various elements of an OTEC system, the

interaction of those elements with each other, and the resulting structural loads that must be accommodated in the design. Although the analytical techniques have been validated to some degree by model tests, as a specific OTEC system design is developed, additional model tests will be needed to corroborate the predicted interactive responses and resulting internal and interface loadings of the prototype platform and its mooring, water intake and discharge piping, and electrical transmission subsystems.

Geotechnical Considerations

The selection and design of foundations and moorings depend upon the environmental and seafloor conditions. Designs and installations in stable sediments and rocks have been demonstrated by the offshore industry, but not at the maximum depths called for in OTEC designs and for shorter anticipated lifetimes. Gravity systems, drag embedment, and driven pile systems are within the state of practice, except as noted below.

If a slope is unstable, gravity and drag embedment anchors will perform poorly. However, anchors and pile foundation elements founded below unstable zones can usually be designed to resist the lateral loads of unstable sediment layers. Technology of pile anchors for tension leg platforms should be directly applicable.

As the bottom slope increases, it may be necessary to prepare the site prior to driving piles. Under some conditions, prefabricated templates will be required.

In deep water, soil conditions could be encountered that differ from those previously experienced to the point that the validity of existing design tools could be questioned. Special studies in these cases needed to confirm the validity of existing design tools or to develop new ones.

The Installation, Operation, and Maintenance of Submerged Power Systems

The design of configurations in which the power system is installed below the sea surface must attend especially to the accessibility of power system components requiring inspection, maintenance, repair, or replacement. The development of design solutions for such requirements are state of practice.

Major System Connections

The OTEC plant design must allow for the planned interruption of operations in severe environmental conditions. If system design is to permit separation of major elements (e.g., platform from cold water pipe or mooring) new design approaches will be needed. Extensive design, analysis, and engineering development will be required, especially to scale up to a 40-MWe prototype OTEC system.

Availability of Platform and Subsystem Materials

Materials for platforms, mooring, and foundation components are generally available. There is significant precedent for conventional steel fabrication of platforms with a 30-year service life at sea. Concrete is also a possible construction material, but the U.S. marine community does not have as much experience in the design and fabrication of large concrete structures for marine uses.

Site Specificity of Design

The effective conceptual design of a prototype system is not possible without thoroughly understanding the oceanographic, meteorological, and geotechnical conditions that prevail at the selected site. Relatively long lead times are necessary to obtain the required data. Where there is general geologic instability in the site area, seismotectonic activity must be predicted to accommodate them in the design.

Slope stability is a major site-specific concern. If unstable conditions are known, they may be avoided altogether or allowed for in the design, though possibly at great cost. Should a particular installation (such as a cold water pipe in a platform configuration) be site-limited, then the cost of a foundation to surmount an unstable condition may become a controlling factor. New devices that more accurately measure slope stability and sediment transport characteristics would permit more accurate assessment of marginal sites. These devices also could be used to correlate field performance with sediment properties and recordings of high resolution geophysical data.

Effect of High-Voltage Transmission on Platform Materials and Corrosion Devices

The transmission of electric power will create a variety of complex ground and fault circuits. It is possible that these will adversely affect the platform and other system components by aggravating active galvanic corrosion and other electrochemical processes. In addition to aggravating corrosion, a high voltage on the structure could diminish material ductility (because of hydrogen embrittlement) and increase brittle crack growth rate. This problem will require special attention during the design, construction, and operation phases of a prototype OTEC plant.

System Selection

The following comments on system selection are presented in order of increasing engineering risk.

- Shore-Based Configurations The land-based OTEC plant differs from conventional construction only by the difficulties it presents for installing and maintaining intake and discharge piping. It offers least risk but is limited in application to a few sites. Research on the platform structure is not required.

- Shelf-Based Configurations Offshore oil industry experience indicates that current technology is sufficient for constructing platforms on the continental shelf. The mass and surface area of those elements of the power generating equipment that will be below the water surface need to be carefully considered in site selection and in subsequent design. Little additional research is required for platform and foundation design. Problems of slope stability deserve special attention.

- Floating Configurations

  - Grazing Configurations Grazing plant-ships may be strongly constrained by product manufacturing systems. Consideration must be given to motion limitations, variable loads, and the transfer of raw materials and products.

    There is adequate technology to design the product plants, but further development of specific components will be necessary. Further research is not warranted until design requirements of candidate industrial processes have been defined.

  - Floating-Moored Configurations In general, there is technology to design and construct suitable platforms and mooring systems. The construction and installation of complex configurations such as a spar would be more difficult than the construction of more conventional ship-shape and semisubmersible hull forms.

  The attachments and interfacings of the platform with the intake and discharge pipes, the submarine electric cable system, and moorings need to be ocean engineered. Preliminary studies have been made of approaches that decouple the heave and motion of the platform, the cold water pipe, and the submarine electric cable system. A considerable advantage could result from such design features.

Computer programs and model testing procedures have been developed to reduce the engineering risk in designing prototype hardware. Further work may be required for the design of a prototype floating platform.

Design Choices

OTEC seawater systems include the machinery, pipes, and hardware used to pump and circulate large volumes of cold and warm water through the power generating plant heat exchangers. To move the massive quantities of water, related plant subsystems and components must be large; the largest component needed is the cold water pipe, which is the focus of this analysis.

For a floating 40-MWe plant, the cold water pipe would be approximately 1,000 m long and 10 m in diameter. A pipe from a land-based or fixed facility would be installed along the ocean floor like a pipeline. Pipes installed along the ocean floor might encounter slopes of up to 40 degrees, be as long as 3,000 to 5,000 m, and (for a 40-MWe plant) have a diameter of 10 m. A pipe of this magnitude has never been fabricated for marine use nor installed in the ocean. The largest analogous pipelines, sewage outfalls, are typically less than a meter in diameter. The largest sewage outfall, off Los Angeles is about 4 meters in diameter, and extends more than 5 miles offshore to a depth of about 60 meters.

The warm water intake pipe will be shorter, about 100 m. The submerged pipes for the seawater discharge system must be sited to avoid reingestion at the cold and warm water intakes. Thus, the location, depth, length, and design of the discharge system pipe may be as important as that of the cold water pipe. Analysis of local heat transfer and diffusion in the vicinity of the OTEC platform will be crucial in specifying these components.

Recognizing the complexity of seawater system design, the panel identified areas in which seawater system design criteria are needed, and their range. The panel also identified technical issues in the development of seawater systems and their status. It did each of these tasks separately for shelf-mounted seawater systems and suspended or floating (in the water column) seawater systems. This material is presented in Tables 2-5. These tables should be considered as preliminary specifications which require further analysis and development.

Table 2 Areas in which Design Criteria are Needed and the Range of Possible Criteria for Shelf-Mounted Seawater Systems

AREAS IN WHICH DESIGN CRITERIA ARE NEEDED	RANGE OF POSSIBLE CRITERIA
1. Near-Shore*	Site specific; shore environment considered to be unproblematic provided an adequate weather window exists for pipe-laying operations.
a) Sea Surface Penetration	
b) Geotechnical Conditions	
c) Topography	
d) Tidal and Current Conditions	
2. Offshore**	Site specific
a) Distance or Pipe Length	2 to 8 km
b) Depths - Topography	Top of Pipe: 0 to 100 m Bottom of Pipe: 500 to 1,000 m Slopes: 25^{o} to 45^{o} Spans: Common peaks in topography of 50 to 150 m or typical topographic trough maximums.
c) Weather and Waves	
i) Deployment Window	Depending on the complexity of the operation, extended periods of good weather are required for deployment.
ii) Operation-Maintenance	Accurate weather forecasts required for surface operations during maintenance.

Table 2 Areas in which Design Criteria are Needed and the Range of Possible Criteria for Shelf-Mounted Seawater Systems (Continued)

AREAS IN WHICH DESIGN CRITERIA ARE NEEDED	RANGE OF POSSIBLE CRITERIA
iii) Survival	To be defined.
d) Current Profile	1/2 to 1 kt along seafloor
e) Geotechnics	Important Unknown for most sites; a year or more lead time required for acquisition of technical data.
f) Biology	Impact on screen designs.
3. Scale for a 40-MWe Plant	3 to 5 m^3/sec/MWe flow (nominal) 10-m diameter pipe or equivalent hydraulic radius (nominal)
4. Interface with Subsea Connection	Needs to be defined; repair and installation are critical; the design must isolate the riser section from the down-slope section of the pipe to accommodate thermal and seismic loads.
5. Discharge System	May have to compete for bottom locations with cold water pipes. May have to accept "second best" site. Thermater effects may require long discharge line.
6. Installation	Needs to be defined. Some data available for smaller components on flatter slopes and in shallow water depths.
7. Maintenance and Repair	Needs to be defined.
8. Availability	To support a system life expectancy of 30 years. Continuous operation on the order of 95 percent availability are required to achieve 70 percent system availability.

*/Near-shore environment covers the area at or near the shelf-mounted platform and shoreward.

**/Offshore assumed to be on the slope and seaward beyond the connection with the shelf-mounted platform.

Table 3 Areas in Which Design Criteria are Needed and the Range of Possible Criteria for Suspended or Floating Seawater Systems

AREAS IN WHICH DESIGN CRITERIA ARE NEEDED	RANGE OF POSSIBLE CRITERIA
1. Near-Shore	Does not apply.
2. Offshore	
a. Pipe Depth	700 to 1,000 m
b. Depth	Site specific. Assume water depth is 50 m greater than pipe inlet depth within 1-km radius circle for sand ingestion considerations.
c. Weather and Wave Conditions	
i. Deployment Window	Requires 1to 2-year lead time for data acquisition; site specific.
ii. Operation-Maintenance	Critical criteria, requires considera- tion of frequency sensitivity of plat- form and cold water pipe.
iii. Survival	Criteria needed for deployment, disconnect, reconnect of cold water pipe and survival with and without cold water pipe attached to platform.
d. Current Profile	1 to 3 kt maximum surface current; site specific; exponential decay, planar profile is a conservative assumption, coplanar with waves.
e. Geotechnical Conditions	1 or more years lead time may be required for acquisition of data.
3. Scale for a 40 MWe Plant	3 to 5 m^3/sec/MWe flow 10-m diameter pipe or equivalent hydraulic radius.
4. Interface with Platform	
a. Non-detachable	Survival conditions required.
b. Detachable	Maximum operating conditions needed plus detachment and reattachment condi- tions.
5. Discharge System	Since cold water pipes will be located at the point of "least action," discharge pipes will be located at a less favorable point which translates into a more severe motion environment than for the cold water pipe.

AREAS IN WHICH DESIGN CRITERIA ARE NEEDED	RANGE OF POSSIBLE CRITERIA
6. Installation	Critical design consideration; considerable experience in deploying similar structures of smaller size and shorter length. Need to determine whether special vessel will be required for installation.
7. Inspection, Maintenance, and Repair	Needs to be developed.
8. Availability	Availability must be high in order to support a system availability of 70 percent over 30 years.

Assessment of Technical Issues

Tables 4 and 5 outline the status of issues concerning development of OTEC seawater systems.

The majority of the technical issues listed in Tables 4 and 5 involve the development of technology and demonstration of engineering feasibility. Nevertheless, some engineering unknowns require long-term data acquisition or additional ocean engineering research for their resolution. Ocean engineering unknowns for shelf-mounted seawater system concepts are:

- Site-specific oceanographic and geotechnical data to establish design requirements.

- Techniques to install foundations and pipes on slopes and in deep water. There is relatively little experience in installing and maintaining foundations for cold water pipes on slopes of 10 to 40 degrees down to depths of 1,000 m with the attendant requirement for long-term stability over 30 years. Installing and maintaining foundations and cold water pipes on such slopes, especially in deep water, may require special handling equipment and techniques. Techniques for measuring slope stability under these conditions need to be developed.

Ocean engineering unknowns in suspended or floating seawater system concepts are:

- Site-specific oceanographic and geotechnical data to establish design requirements.

- Design of the interface between pipe and platform. The design choices for this interface are to separate the pipe and platform, connecting them with a yoke (see preceeding section on platforms); or, to suspend the cold water pipe from the platform, employing a heave-compensated gimbal.

- Analysis of constraints imposed by pipe installation procedures. The float out-flip up design is sensitive to operating procedures, while vertical assembly requires long weather windows. The float out-flip up design deploys faster and would therefore be more suitable where weather windows are shorter.

TABLE 4 Technical Issues in the Design of Shelf-Mounted Seawater Systems

TECHNICAL ISSUE	STATUS
1. Connection to Condenser	Concepts defined: no detailed design effort begun; isolation required in design to reduce dynamic motions between pipe and platform due to thermal and seismic loading.
2. Pipe Configuration	
a. Straight	Sensitive to topography (SOP).*/
b. Buoyant Suspended	Sensitive to current loads.
c. Contour Following, Articulated	Concepts defined, no detailed design effort begun.
d. Tunnel	Sensitive to geotechnical conditions.
3. Pipe Connections	
a. Fused (grouted, glued, welded, potted)	Depends on material and method of deployment.
b. Mechanical	Depends on material and method of deployment.
i. Rigid	
ii. Flexible	Critical element.
4. Pipe Material	
a. Steel	SOP.
b. Reinforced Concrete	SOP.
c. Fiberglass-Reinforced Plastic	SOP is 3-m diameter. Requires impact strength development.
d. Polyethylene or PVC	SOP is 3-m diameter.

	TECHNICAL ISSUE	STATUS
5.	Seawater Discharge System	Must compete for location with the cold water and warm water intakes.
6.	Installation	Sensitive to environmental conditions (currents, weather); needs step-by-step operational analysis.
7.	Foundation	Specifications require geotechnical data.
8.	Loads Criteria	Needs environmental data. Fatigue life critical for fiberglass reinforced plastic configurations. Computer design aid ROTECF**/ needs experimental validation to translate into a shelf-mounted pipe analysis. Foundation stability critical.
9.	Inspection, Maintenance, and Repair	Failure mode effects analysis required.
	a. In Place	New maintenance techniques required below 200 m. Fiberglass-reinforced plastic repair techniques need to be developed for all depths.
	b. Recovery and Replacement	Procedures need definition.

*/The term "state of practice" (SOP) means that no additional engineering research is necessary; the issue is confined to a design problem.

**/A frequency domain computer program for computing platform motions for floating structures.

TABLE 5 Technical Issues in the Design of Suspended or Floating Seawater Systems

TECHNICAL ISSUE	STATUS
1. Connection to Floating Platform	Critical element. Requirements for detachment need to be established including those for the design of rigid and flexible connections, and those that account for fouling and local buckling.
2. Pipe Configuration	
a. Continuous, Rigid Joints	SOP in steel. SOP for fiberglass reinforced plastic is 3m diameter pipe. Dynamic loads make application of concrete questionable.
b. Articulated	Joint maintenance critical.
3. Pipe Connections	
a. Fused/Bonded	SOP for steel welds; steel needs to be stress-relieved. SOP for fiberglass reinforced plastic is manufacturing ability for 3m diameter pipe.
b. Rigid, Mechanical	Likely to be critical fatigue area.
c. Articulated	Joint reliability.
4. Pipe Material	
a. Steel	SOP, heavy, has marine experience, requires corrosion protection.
b. Reinforced Concrete	Heavy, inappropriate in dynamics, needs articulation, narrow stress range, and low strain range.
c. Fiberglass Reinforced Plastic	Requires development, long-term fatigue and impact resistance not established.
5. Seawater Discharge System	Must compete with the cold water pipe and warm water intake.
6. Foundation	Applies only to tension leg cold water pipes and affects dynamic stresses.
7. Installation	
a. Float Out Flip Up	
i. Construction/Transport	SOP except for diameter size.
ii. Placement and Connection	Critical stress on pipe.

b. Sequential Vertical Assembly	
i. Construction/Transport	SOP.
ii. Placement	SOP, except weather-sensitive for physical parameters of cold water pipe response that change during pipe erection cycle and field joint makeup, and effects on platform configuration. Weather windows must be determined and requirements specified for larger handling equipment and platforms.
8. Loads Criteria	
a. Hydrodynamic Loads	Vortex-shedding critical fatigue problem, suppression devices need careful study.
b. Dynamic Loads (Ship/ Wave Induced)	ROTECF* has been adequately validated, although without vortex input. SOP, care in selecting the range of force frequencies.
c. Handling and Installation Loads	May be critical failure mode.
d. Motion Effects on Seawater System	Seawater system analysis needs validation. More critical for warm water loop.
9. Inspection, Maintence, and Repair	Analysis required of failure mode and possible effects.
a. In Place	SOP to 200 m. New maintenance techniques required below 200 m. Fiberglass-reinforced repair techniques need to be developed for all depths.
b. Recovery and Replacement	Procedures need definition.
10. Instrumentation	
a. Stress	SOP.
b. Motions	SOP.
c. Flows and Pressures	SOP.
d. Fouling Rates	SOP.

*/ A frequency domain computer program for computing platform motions for floating sturctures.

- Requirements for suppressing vortex-induced vibration, and development of suppression devices. Moderate currents could lead to extreme vibrations of the pipe unless suppression devices are installed. These devices will increase drag, however this trade-off needs further study.

Techniques for detaching, jettisoning, or recovering suspended cold water pipes require study in order to create proper system survivability characteristics and platform maintenance procedures in conjunction with cold water pipe operating stresses.

To identify and resolve seawater system engineering development items, there is a need to prepare integrated OTEC system designs. Design analysis and validation plans are also necessary. Data bases in the following areas need to be developed as an element of overall system design and integration:

- Long-term material properties of fiberglass-reinforced plastic under the operating conditions of OTEC structures.

- Inspection, maintenance, and repair procedures for alternative seawater designs (e.g. FRP pipe).

While most of the technical issues in developing discharge pipes are like those in developing the intake pipe, some are unique to the discharge system. Discharge pipes must compete with both the cold and warm water intakes for the best site (from a geotechnical standpoint if in the form of a pipeline, and with regard to minimum motion if floating). The designer may have to choose between the separate discharge of warm and cold seawater or their mixed discharge. Separate discharge means more pipes competing for favorable locations. In a mixed discharge system, the discharge pipe must be large to reduce plant losses, or if losses are acceptable, the discharge velocity must be high. Higher discharge velocities result in hydraulic reactions at the discharge end of the pipe.

Seawater system concepts are applicable to sizes larger than 40MWe pilot-scale; however, their upper limits have not been established. Engineering uncertainties are fewer for shelf-mounted systems than for suspended or floating pipes.

SUBMARINE ELECTRIC CABLE SYSTEM

Design Choices

While OTEC plants may produce a variety of industrial products,[2-5] the focus of this chapter is the design and operation of a system to supply baseload electricity to a regional electric power grid. The submarine electric cable system includes the design, construction, installation, maintenance and repair of multiple high voltage bottom and riser cables (see Figure 4), and their terminations, attachments, protection, and interfaces. The electric cable system of a land-based OTEC plant will have no ocean engineering requirements. Bottom-resting plants require only bottom cables that are semi-rigid and extend along the bottom from plant to shore. Such bottom cables would likely be embedded 2 to 3 m in the seabed from the shore to the 100-m contour, and rest on the seafloor for the remaining distance. However, even in this configuration, the cable will hang in a catenary to accomplish the transition from sea floor to platform.

Moored plants require riser electric cables in addition to bottom cables. The riser cables link moored OTEC plants to the bottom cable on the seafloor. Riser cables must withstand stresses from weight, current drag, strumming, platform motions, corrosion, biofouling and abrasion.

A grazing platform with a fixed electric power cable connected to a shore site is not considered a viable concept.

In both the bottom-resting and floating-moored configurations, cable installation, and inspection, maintenance, and repair may dictate design and construction requirements; for example, the weight and dimensions of the 100-MWe cable the Department of Energy is now designing are such that the installation of the cable in water much over 1,000 m depth exceeds the existing handling capability of any of the current fleet of cable laying vessels. Thus it will be necessary to modify or build a cable installation vessel for the specific purpose of installing the OTEC cables.

The assessment of the OTEC submarine electric cable system that follows focuses on a floating, moored platform concept located close (2 to 3 miles) to a suitable shore connection point.

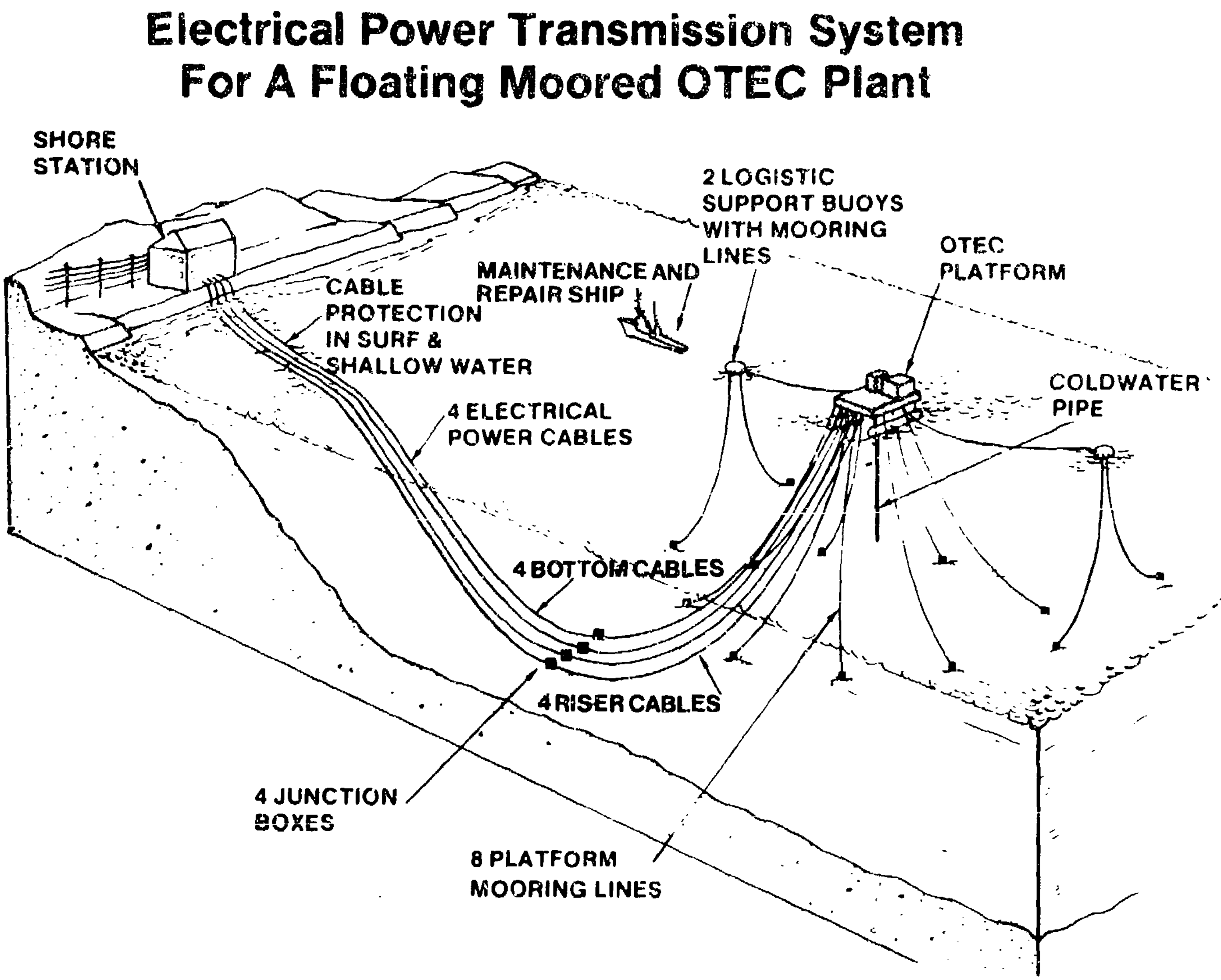


Figure 4 Submarine Electrical Cable System for a Floating OTEC Plant

Assessment of Technical Issues

System Design Requirements

The potential for the submarine electric cable system to meet general OTEC design requirements is as follows:

- o Operability With the exception of installation, which will require periods of fair weather, the requirement of operability in seas up to sea state 6 can be expected to be met.

- o Availability Continuous operations on the order of 95 percent availability are required to achieve 70 percent system availability. (Also see "Life" below).

- o Survivability With proper regard for the integration and careful placement of all OTEC components (particularly those items within the water column such as moorings, cold water pipe, and electric cables), this requirement should be met.

- o Life A riser cable attached to a floating, moored power plant will be subjected to cyclic stresses. Knowledge of the fatigue performance of major cable components is insufficient to predict a 30-year cable life. Under these conditions of stress, the 30-year life goal is deemed unrealistic. Even a 10-year life for the riser cable will be difficult to achieve. If well protected, the bottom cable may achieve a 30-year life. The installation of both the riser cables and bottom cables (especially trenching where necessary) also will be formidable tasks--in most installations to date of high voltage submarine electric cables, the life of the cable has been lessened during cable installation.*

Research and development for the OTEC submarine electric cable system have addressed the satisfaction of a limited set of component-level requirements. The system has not been defined in terms of its functions and interfaces relative to other elements of OTEC plants. A total submarine electric cable system definition must be prepared and the research and development specified for each component that is not currently available. Figure 5 presents a schematic of the submarine electric cable system, and shows interfaces of the system elements. Complete system definition would provide the basis for identifying, defining, and evaluating alternative combinations of equipment, facilities, and procedures.

*Willard F. Searle August 25, 1982. Searle Consortium, Ltd. Personal communication.

Environmental Design Criteria

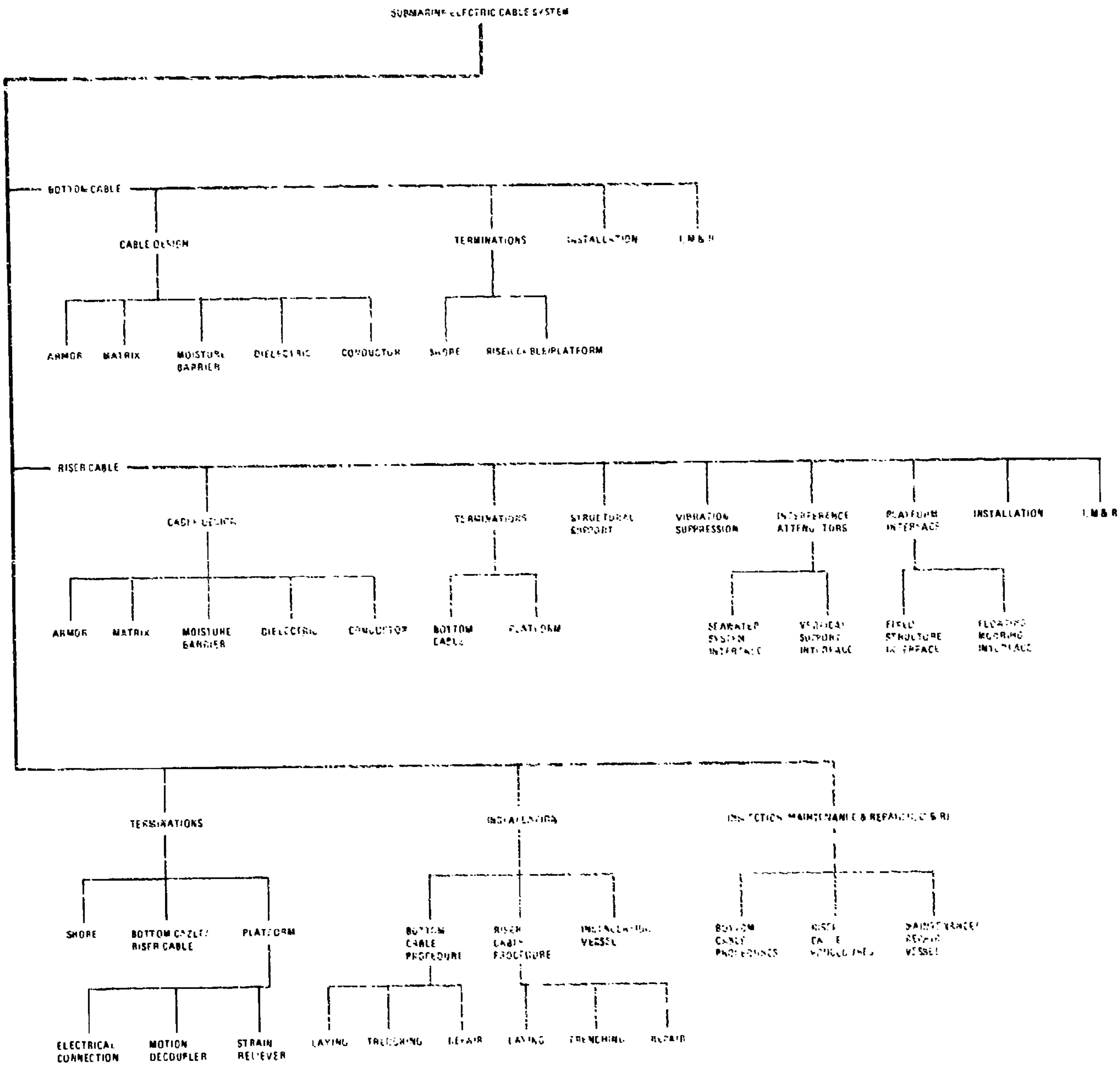
Establishment of environmental design criteria is a necessary element of system design. Every major attribute of the submarine electric cable system, with the exception of its current-carrying capacity, is significantly affected by environmental characteristics of the site. Such attributes include not only the mechanical design of the cable, terminations, and restraints, but also procedures for installation, inspection, maintenance, and repair.

Narrowing the choice of sites and conducting preliminary environmental site surveys would allow the establishment of far narrower requirements. In turn, the more specific requirements would allow submarine electric cable system development to be better focused, and would reduce dead-end research or overdesign. Overdesign of the dimensions and weight of the cable would have very significant impacts on the cost and feasibility of installation.

Adequacy of Riser Cable Design Effort

The major design concern is the riser portion of the submarine electric cable system. While a fixed or supported cable may well achieve a 30-year life, this goal is unrealistic for a riser cable connected to a floating OTEC plant. A riser cable attached to a floating, moored power plant will undergo simultaneous exposure to cyclically varying tensile stresses, torquing, bending, and electrical stresses. No submarine electric cables to date have been subjected to such an application; they are usually fixed on the seafloor. Knowing the fatigue performance of major cable components (armor wire, lead hermetic sheath, insulation, and electrical core) is not sufficient to predict a 30-year cable life confidently. Even a 10-year life is unlikely.

Figure 5 Submarine Electrical Cable System



The riser cable to a fixed platform will be static, eliminating fatigue as a major area of concern. While some problems such as the effects of a long vertical drop on cable integrity, may remain for design of the riser cable in this application, they are considered less severe than those noted above. A 30-year life for a riser cable to a fixed plant may thus be possible.

For floating configurations, cable replacement at intervals, perhaps every 10 years, must be considered. Fatigue characteristics of the cable and its components require systematic study. For fixed platforms, research is required on the effects of long vertical drops on cable performance and lifetime (analogous situations may be found in mine shafts or tunnels associated with hydroelectric plants).

Priorities and schedules for cable system development cannot be developed or reviewed until equipment specifications and site conditions are better defined. The development required for cable installation needs 2 to 4 years; for inspection, maintenance, and repair, 3 to 5 years. If cable design and validation by testing will require development of massive equipment, 6 to 8 years lead time will be necessary.

Adequacy of Overall Submarine Electric Cable System Development

Life-cycle requirements for the submarine electric cable system under development by the Department of Energy have not been adequately defined or considered for functions such as installation; inspection, maintenance, and repair; point and distributed loads for support and anchoring; and interfaces such as terminations or connections onshore, between the bottom cable and riser cable segments, and between the riser cables and the OTEC platform. Similarly, trade-offs between the number of cables, the weight and dimensions of cables, and the availability, capacity and cost of cable installation vessels have yet to be fully addressed. The submarine electric cable system life-cycle requirements require further definition of mission objectives, system elements and their operational scenarios and functions, design criteria, and operational need dates.

Cable Size

The cable designs being developed under contract to the Department of Energy would carry 100 MWe at 138 kilovolts. These cables may be overdesigned for a 40-MWe plant. Their weight would exacerbate the already difficult problems of their installation and inspection, maintenance, and repair. The 100-MWe cable may also be unnecessarily expensive for use with a 40-MWe plant.

Still the weight and cost advantages of special 40-MWe riser cables need to be investigated. Such special cables could significantly reduce cable and installation costs and electric power losses over the system lifetime. Two concepts for a 40-MWe riser cable system are likely: a system of approximately four single-conductor cables; or a system of one or two three-conductor cables.

Metal Fatigue Properties

The Department of Energy is conducting research on cyclic loading, corrosion, corrosion fatigue, the fatigue properties of the lead hermetic sheath, and the effects of combined mechanical and electrical stress on the aging of dielectric materials. These investigations may lead to significant advances in cable materials technology. However, these investigations have not yet demonstrated that riser cables attached to floating platforms can suitably perform in the OTEC environment over extended periods of time; that specifications for a cable with a 30-year life can confidently be prepared; nor that the cable design that has been developed can be manufactured in the U.S. or abroad. Additional research in each of these areas is needed for the data base development of he submarine electric cable system.

Slippage

Slippage of the electrical core of a paper-insulated, oil-filled cable within the external armor held in a long vertical suspension is a problem that may require an advance in cable technology.

"Clamping" of the core by radial compressive forces from armor wires and from hydrostatic pressure needs investigation to determine its value as a technique for resisting slippage. The extent to which the slippage problem will be aggravated in oil-filled cables also needs to be determined, as should the potential of highly viscous impregnating oils (in mass-impregnated cables) to alleviate slippage.

Field Connection

Should the riser segment of the cable system fail, then either it alone or the entire cable run from platform to shore will need to be replaced. The re-lay to repair procedure, if technology exists for initial installation, would not require additional technology development (but would certainly be very costly). Riser cable replacement, however, demands an interconnection point with the bottom cable or the development of field repair and splice techniques. No bottom-founded interconnection or field repair technology exists at present for high voltage, high current submarine cables.[6] The technologies for cable repair and replacement and the life costs of alternate repair and replacement strategies need to be specified.

System-wide Corrosion

Many metals exhibit good short-term corrosion characteristics, but constant contact with the seawater environment can alter material properties. Stresses and strains induced in the metallic armor also may cause some changes in their alloy metals, thereby accelerating the effects of corrosion. These long-term effects require more accurate assessment.

There is probably no valid test of the effects of corrosion that uses accelerated time testing methods and that takes into account all necessary factors. The present tests and studies of submarine electric cable armor tend to examine shortor long-term corrosion without considering the effects of bending and other stresses.

Electrostatic or galvanic corrosion, which is enhanced by the electric fields of currents in the cable, also requires investigation, as does the effect of the electric field from the high-voltage cable on both the passiveand impressed-current cathodic protection systems for the steel platform members. Also requiring study is the possibility of additional corrosion from the electric and magnetic fields the cable generates when energized.

Hazards From Large Animals

Large marine animals present a potential hazard to a cable carrying electric current from the plant to the seafloor. There is a significant body of evidence to show that sharks and large fish are attracted to, and will damage by biting, cables rated at much lower voltage than those OTEC requires. Little is known about the susceptibility of high voltage submarine cables to animal attack. Large sharks are known to be able to apply sufficient tooth pressure to deform or penetrate the armor wires and breach the watertight integrity of the lead sheath of submarine telecommunication cables resulting in the complete failure of the cable. The behavior of large marine predators toward alternating and direct current high voltage submarine cables needs to be established.

Cable Design Analysis and Validation

The design of the cables heavily depends on computer models that require validation through testing. The riser cable has a very complicated loading pattern that varies both with time and with distance along the cable. Computer modeling is the only practical method to study stress distribution along the cable length. Such computer models involve advanced techniques of analysis and have received only limited validation from mechanical testing of sections of prototype

cables. The unvalidated or insufficiently validated elements of the analytical tools need to be identified. Laboratory-instrumented mechanical tests should be executed to validate these models or to provide calibrating coefficients. Full-scale, at-sea tests of complete riser cables should be used as a design verification tool.

Gimbal Design

The mode of termination and system of strain relief required to decouple the platform loads from the riser cable requires special attention because both mechanical and electrical constraints are involved.

The termination of the riser cable at a floating platform presents a wide range of conflicting design requirements for a gimbal device, one that is not available with current technology. Available gimbal devices, for example, do not allow for constant motion under high stress loads while carrying high voltage and current. In addition, the gimbal must reliably operate for extended periods.

Further design complications arise from: cable chafing and stress at attachment points; loss of efficiency in strain relief systems over time; threat of failure at cable terminations; necessity of providing for some maintenance and repair, such as bearing replacement, without power interruption; and safe decoupling, if called for in the design.

A conceptual design and verification of the critical elements of the gimbal is needed. Based upon the results of this effort, a decision may be made about the necessity for an advanced gimbal development program.

Installation

Great importance must be given to the cable's installation. For the cables under development by the Department of Energy, a cable laying machine capacity of just over 100,000 lb would be required to install the cables at 1200 m depth; about 150,000 lb capacity would be required to install the cables at 1800 meters depth.* At least one existing cable installation vessel, the Skaggerak, is equipped with a laying machine that has about 100,000 lb tension capacity, and thus could install the OTEC cables at depths approaching 1200 m. Other factors enter the picture, however; cables designed for deep water installation are torque-balanced and cannot be coiled. The Skaggerak is the only cable installation vessel with turntable facilties for

* James Soden, Simplex Wire and Cable Company, personal communication, August 19, 1982.

storing and handling torque-balanced cables. The overboarding sheave and cable machine capstan diameter of cable installation vessels is also a concern; the Skaggerak is currently fitted with a sheave and capstan adequate for installing the OTEC cables. Since the capabilities of existing cable installation vessels do not completely match OTEC requirements, and since the few existing vessels are scheduled years in advance, it will be necessary to modify an existing cable installation vessel, or to construct a purpose-built OTEC cable installation vessel in order to install OTEC cables at depths greater than about 1000 m.

For bottom cables, maintaining cable separation, performing site surveys, and controlling cable location do not appear to present any problems outside of the realm of the available technology, assuming that suitable cable handling equipment is available; however, available instrumentation for this might require some modification.

A step-by-step analysis is required to identify the procedures for cable installation and to define further the support equipment necessary to do the installation. In turn, the type of OTEC platform, fixed versus floating, and the details of the cable installation for each, will have major impact on cable design. Cable system installation requirements would be different and possibly less for fixed platforms, which would not have a riser cable.

Cable Protection

Some submarine electric cables are buried to protect them from damage that might result from bottom dragging equipment of trawlers or from the chafing action of current-induced motions. For some OTEC sites, cable runs in areas of steep and rocky slopes may pose additional hazards. Sloped sites may have inadequate material for burial, or may be unstable over the long term. Protection may be applied by coverage with overburden (a common practice of dumping rocks or gravel onto cables that cross rocky areas). However, existing methods for cable burial may not provide sufficient protection for the submarine electric cable system in the unstable areas. Further investigation of cable burial coverage by overburden systems is necessary.

A review should be made of available oceanographic and geotechnical data from potential sites, followed by a systems study of cable protection requirements including an assessment of existing methods and equipment, and identification of needed modifications to current designs and of new design concepts.

Inspection, Maintenance, and Repair

Systems for inspection, maintenance, and repair of the cable in both shallow and deep water are critical. Sensors of the cable's condition, and the means to apply them, need to be developed. Repair and maintenance protocols should be established, and the necessary supporting equipment identified. Should a cable have to be retrieved or repaired, it will be necessary to have available specially designed platforms and equipment; this needs to be addressed during the design of the system.

Inspection Shallow water inspection can be accomplished with present technology. Inspection in deeper waters can be accomplished with remotely operated vehicles, but these vehicles can identify the cable's condition and problem locations only if the cable is visible.

Existing methods for locating nonvisible faults in cables rely on knowing the cable's electrical characteristics and using state-of-the-art instrumentation to measure cable impedance to the fault. It also may be possible to use the faulted cable section as a radiating antenna for determining the fault locations. These methods of locating faults are in current use.

Cable inspection equipment and certain sensors will still require an extension of available technology. It would be desirable, but not necessarily practical, to monitor the cable strain and bending stress especially in the riser section of the cable. To withstand environmental forces and conditions imposed on the cable, and to achieve its desired life, advances in inspection technologies are needed.

Cable Repair Requirements for the repair of submarine electric cables differ in several ways from cable installation. A cable installation vessel must be capable of storing a cable length and be equipped with machinery to pay the cable out and lay it in the ocean, or on (or beneath) the seafloor. In preparing for the laying operation it is possible to make many preparations in advance. Where installation involves only lowering the cable, repair may require both raising and lowering. Cable splicing onboard a repair vessel can be time-consuming -- an extended period of fair weather may be necessary. During the period in which a cable is raised for repair, the cable armor will be subject to cyclic loading and fatigue may be a problem.

When faults in cables are detected after installation, a decision must be made as to the economics and reliability of repair or replacement. Should repair be indicated, one of three strategies may be employed.[7] A problem at a finite point can possibly be corrected by cutting through the cable at the defective point, then splicing the ends. Since this procedure shortens the cable slightly, it increases

the tension of the system. A second strategy for use when a section of cable must be removed is to splice in a new section. This procedure requires two splices. The new cable length will be longer than the piece removed. When the spliced cable is reinstalled, the extra length will form a loop on the seafloor. This loop or "dutchman" cannot be installed under tension (as the rest of the cable is), and it may not rest as securely on the seafloor as the original cable; thus the "dutchman" may be more vulnerable than the rest of the cable to subsequent damage. A third approach to repair is to retrieve the damaged cable from the point of damage to the shore, to splice in a replacement length, and then to re-lay the repaired cable. A field connection or splice for underwater cables is integral to each of these strategies, and therefore is necessary as an economic alternative to replacing the cable.

The maintenance and repair requirements for riser cables will require technology development and need to be established. A step-by-step analysis is needed to identify the required procedures and to define requirements for related support equipment. Since the panel commenced work, an OTEC inspection, maintenance, and repair study has been initiated that may resolve many of these difficulties.[8]

INTERACTION BETWEEN THE TECHNOLOGY BASE AND SYSTEM SELECTION

To proceed with the design and ocean engineering development of a 10 to 40-MWe OTEC plant, several key unknowns need to be resolved:

- Determine the location and type of plant (e.g., floating, shelf-mounted, or land-based).
- Establish environmental design criteria.
- Establish plant capacity based on realistic estimates of energy demand, available technology, and site-specific environmental criteria.

Systems integration is necessary for continued development of OTEC plants. Systems integration describes the process of melding separate technologies into a unified system to achieve stated objectives. Choices are made in systems integration between alternatives; for example, among candidate sites, platform types, construction materials and facilities, and installation techniques. In systems integration, it is necessary to specify locations for OTEC plants in order to begin acquiring environmental exposure data and establishing design criteria. It is also necessary to consider the interfaces between OTEC components, their design requirements, and interactions. These interactions include the cold water pipe and the platform, the electric cable and the platform, the industrial plant and the oceanic structure which supports it, and the dynamic interactions of the OTEC plant with the physical environment. Initial installation, and subsequent inspection, maintenance and repair considerations are controlling elements of systems integration.

While many of the needed developments identified in the previous sections will be resolved through the normal engineering processes of systems integration and design, some OTEC systems need additional engineering development. The cold water pipe and electric cable systems especially require attention:

- Techniques for manufacturing, installing, inspecting and repairing the large diameter cold water pipe and the bottom and riser electric cables need to be tested. Material properties under long-term ocean conditions need to be determined. Techniques for field maintenance need to be developed.

- The potential for vortex shedding and vibrations of the cold water pipe need to be studied and suppression devices tested which will reduce flow vibrations need to be tested. On the cold water pipe, vortex suppression devices could increase drag significantly. The effect of the added drag on the pipe connection to the platform and on mooring loads needs to be assessed.

- Mathematical models for the combined motions of the platform and the cold water pipe need to be calibrated through laboratory or offshore tests on prototype designs.

- Fatigue of electric cable materials subject to long-term ocean exposure needs ocean engineering research.

- Impact of power transmission on system corrosion needs to be studied.

- Methods for inspection, maintenance, and repair of riser cables need to be developed.

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APPENDIX A
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    Bryant Engineering, Incorporated
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Harold Chester
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APPENDIX B

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